Frequency-Difference Source Localization and Blind Deconvolution in Shallow Ocean Environments

David R. Dowling
Department of Mechanical Engineering
University of Michigan
Ann Arbor, MI 48109-2133
phone: (734) 936-0423 fax: (734) 764-4256 email: drd@umich.edu

Award #: N00014-13-1-0115
http://www.personal.engin.umich.edu/~drd/

LONG-TERM GOALS

The overall long-term goal for this project is to develop engineering tools that are useful to the Navy as it operates in uncertain, partially known, or unknown ocean environments. During the last year, this project has focused on (*i*) extending the synthetic time reversal (STR) blind deconvolution technique to dynamic multipath environments, and (*ii*) determining the utility of the frequency difference concept within matched field processing (MFP) as a means of robust source localization with sparse arrays and high frequency signals in imperfectly known environments. If successful, the STR work might make underwater acoustic communications more efficient and reliable since sound-channel calibration would not be necessary. Successful frequency difference MFP might extend the Navy's current sound source localization and tracking capabilities.

The long term goals of this project are: *i*) to determine the effectiveness of STR for the purposes of blind deconvolution in dynamic noisy unknown ocean sound channels, and *ii*) to understand and quantify the utility of the frequency-difference concept for remote underwater source localization when applied to MFP. Progress this year has primarily been made toward goal *ii*) so it is emphasized in this annual report.

OBJECTIVES

Since early 2009 this project has focused on developing an acoustic-ray-based version of synthetic time reversal (STR), a fully-passive technique for recovering the original signal and the source-to-array-element impulse responses for a remote unknown sound source in an unknown underwater waveguide [1,2,3]. Along the way, a new method for beamforming (frequency difference beamforming) [4] and a new method for ranging marine mammal calls [5] were developed. The current specific objectives are to: a) assess the performance of STR using 4-by-4 planar hydrophone array recordings in a reverberant laboratory water tank, and b) assess and understand the performance of frequency-difference MFP using ocean propagation measurements made as part of the Kauai Acomms MURI 2011 (KAM11) Experiment. This research effort extends the work on STR to different array configurations, different reverberation levels, longer duration signals, and (possibly) dynamic environments; and extends the prior frequency-difference beamforming work into the realm of MFP.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2014**	2. REPORT TYPE	3. DATES COVERED **00-00-2014 to 00-00-2014**

4. TITLE AND SUBTITLE **Frequency-Difference Source Localization and Blind Deconvolution in Shallow Ocean Environments**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Michigan,Department of Mechanical Engineering,Ann Arbor,MI,48109**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

APPROACH

Over the last year, this project has focused on understanding and simulating STR with extended duration signals, which are common in current underwater communication schemes, and on understanding and simulating frequency-difference MFP. In both cases, enough understanding was developed and sufficient success was achieved with simulations so that the investigations have moved on to performance tests with array-recorded sounds. The array-recorded sounds for the STR effort come from a 1.07-m-diameter 1.0-m-deep laboratory water tank in which 50 kHz center frequency communication sequences are broadcast to a 4-by-4 planar hydrophone array. This experimental work was completed with the help of an undergraduate student team and was supported by NAVSEA through the Naval Engineering Education Center. The array-recorded sounds for the frequency-difference MFP investigations were recorded as part of the KAM11 experiment and were provided for this research effort by Dr. Heechun Song of Scripps Institution of Oceanography (SIO). Doctoral students Ms. Jane Kim and Mr. Brian Worthmann (both US citizens) are working on the STR and frequency-difference MFP investigations, respectively.

Frequency difference MFP is a non-linear method for source localization that generates low-frequency signal information from high-frequency signals. Its formulation may be understood when compared to that of ordinary MFP. Recall that ordinary MFP be cast as a weighted spatial filtering,

$$B(\vec{x},\omega) = \left| \sum_j w_j(\vec{x},\omega) p_j(\omega) \right|^2 , \tag{1}$$

where B is the MFP output at location $\vec{x}$ for frequency ω, w_j is the weighting for location $\vec{x}$ and frequency ω for the j^{th} receiver, and $p_j(\omega)$ is the complex pressure at frequency ω recorded at the j^{th} receiver. In (1), w_j is usually produced with the help of a propagation simulation intended to match acoustic propagation in the environment in which $p_j(\omega)$ was recorded.

For frequency difference MFP, the complex auto-product of the recorded field replaces $p_j(\omega)$,

$$B(\vec{x},\omega,\Delta\omega) = \left| \sum_j w_j(\vec{x},\Delta\omega) p_j\left(\omega+\Delta\omega/2\right) p_j^*\left(\omega-\Delta\omega/2\right) \right|^2 , \tag{2}$$

and the weighting function is evaluated at the chosen difference frequency $\Delta\omega$. The complex conjugation of the second field amplitude in (2) causes the auto-product of the field to present propagation information at the difference frequency $\Delta\omega$, a frequency that may lie well below the original signal bandwidth. Frequency difference MFP exploits this synthetically generated low frequency information to more robustly localize the source than is possible using (1) in the original signal bandwidth.

The experimental geometry for the KAM11 measurement is shown in Figure 1. A vertical source array having elements with depths between 38 and 90 m broadcasted 100-ms-duration linear frequency modulated (LFM) pulses with nominal center frequency and bandwidth of 22 kHz and 20 kHz, respectively. The 16-element receiver array was also vertical and was deployed 3 km away between depths of 41 m and 97 m in 106 m of water. It was sparse with more than 50 signal-center-frequency wavelengths between elements. The sound speed profile was mildly downward refracting with surface

and near-bottom sound speeds of 1537 m/s and 1532 m/s, respectively. A thermistor string in the vicinity of the primary propagation plane showed multiple-meter variations in mixed layer depth over the course of a day. Here it must be noted that KAM11 was an underwater communications experiment. Thus, use of KAM11 propagation measurements for a source localization study is unusual.

WORK COMPLETED

The status of the STR and frequency-difference MFP investigations is as follows.

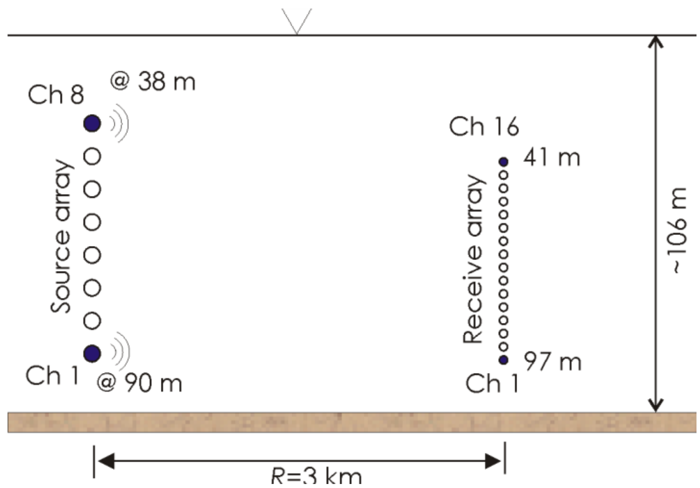

Figure 1. Nominal geomtery of the KAM11 experiments. LFM pulses with a duration of 100 ms, center frequency of 22 kHz, and bandwidth of 20 kHz were individually broadcast from eight different source depths to a 16-element vertical receiving array 3 km away. The sound speed profile in the water column was mildly downward refracting with a ~5 m/s difference between the ocean's surface and bottom.

STR was simulated for a 1 km source-array range in 100 m of water using a Pekeris waveguide modal-sum propagation code,. The signal center frequency was 2 kHz and the vertical receiving array had 16 elements spaced 1.5 m apart. Binary phase shift keying (BPSK) signals with 4 carrier cycles per bit and 1 to 256 bits were broadcast to the array and successfully demodulated (no errors) without a probe signal or a training sequence. Based on this success, the research effort moved on to blind deconvolution of BPSK signals measured in the reverberant laboratory water tank. Initially, STR failed with a 1-by-16 linear array deployed in the water tank environment where there is strong three-dimensional reverberation. The nominal reverberation time in the tank is 10 ms while the time to broadcast one bit is just 0.08 ms (4 cycles at 50 kHz). Thus, the array was reconfigured to a 4-by-4 geometry, some underwater sound absorption material was purchased and placed in the tank, and new measurements have been made. Initial results suggest that the square array better manages the three-dimensional reverberation, and blind deconvolution in this harsh multipath environment may be possible.

Frequency-difference MFP was simulated for source array ranges of 1 km, 2 km, and 5 km in 100 m of water using a method of images propagation code involving 3, 5, or 7 signal paths. The signal was an LFM pulse with 15 kHz center frequency and 10 kHz bandwidth. Difference frequencies from 50 Hz to

1.2 kHz were considered, and Gaussian-distributed random time delays with a standard deviation of 0.1 ms were added to each propagation path to simulate environmental mismatch. The simulations showed that frequency difference MFP, incoherently averaged through 50 Hz $\leq \Delta f \leq$ 1.2 kHz, could reliably localize the source when ordinary MFP from (1) averaged through the signal bandwidth, 10 kHz $\leq f \leq$ 20 kHz, could not.

Based on this simulation success, suitable broadband experimental measurements were sought, and Dr. Song of SIO recommended and provided LFM pulse propagation measurements from KAM11.

RESULTS

Sample results from the simulations of conventional (Bartlett) MFP and frequency difference MFP are shown in Figure 2 for a 1 km source-array range using the LFM signal and sound channel described above. Here conventional MFP averaged through the signal bandwidth fails, but frequency difference MFP accurately locates the source in spite of the random time delays.

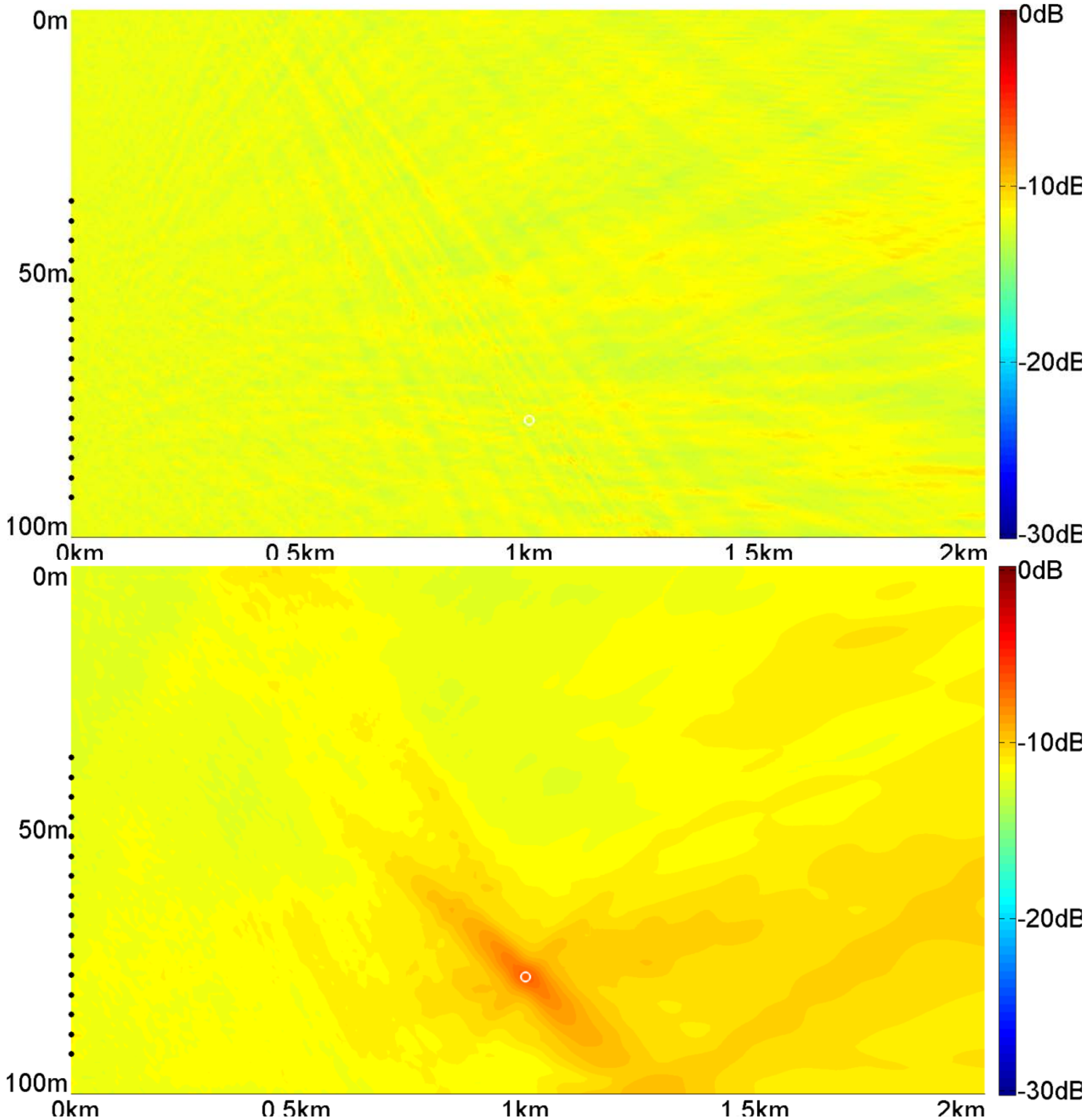

Figure 2. Simulated conventional (upper) and frequency difference (lower) matched field processing results. The source-array range is 1 km, the sound channel is 100 m deep, and Gaussian random time delays with a 0.1 ms standard deviation have been added to each of the propagation paths between the source and each reciever. The receiving array with 16 elements is shown at the left, and the source appears as a white circle. The conventional results were incoherently averaged over the signal bandwidth, 10 kHz ≤ f ≤ 20 kHz. The frequency difference results were incoherently averaged over the signal bandwidth and over 50 Hz ≤ Δf ≤ 1.2 kHz. Conventional MFP fails in these circumstances. However, frequency-difference MFP correctly indicates the source location with a peak-to-side-lobe ratio of 2.7 dB.

Sample results from frequency difference MFP for the KAM11 measurements for a 3 km source-array range using the 12 to 32 kHz LFM signal are shown in Figure 3. The nominal source-receiving array geometry is shown in Fig. 1. In Fig. 3, the array is on the left and again a white circle denotes the actual source location at a depth of 60.2 m. Here the results have been averaged through the bandwidth of the signal, 12 kHz $\leq f \leq$ 32 kHz, and over difference frequencies, 5 Hz $\leq \Delta f \leq$ 1.0 kHz. And, the array element weightings – w_j in (2) – are based on only 4 modes. Interestingly, an MFP peak does appear close to the location of the source, but there are also auxiliary MFP peaks very near the array and at twice the range of the peak of interest. These peaks are at the same depth as the peak of interest and their origin is now under investigation. Overall, Fig. 3 shows an intriguing result since it suggests that source localization is possible at high frequencies with a sparse array in the ocean.

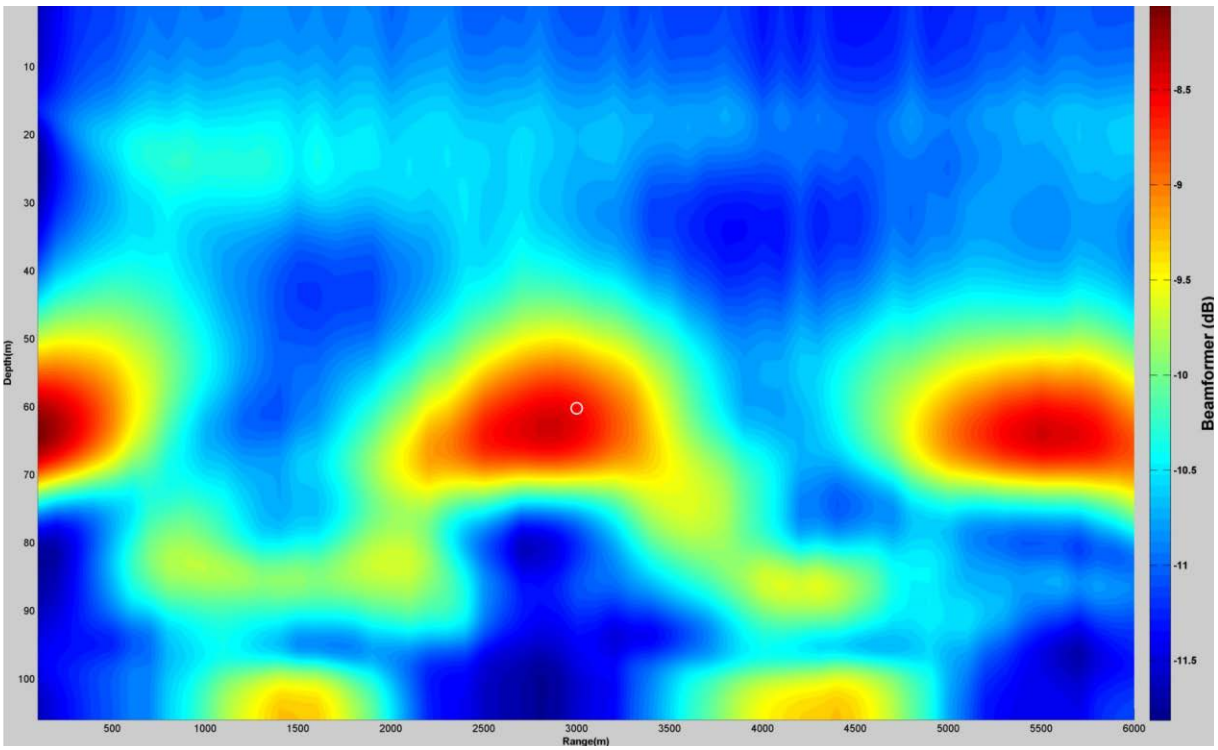

Figure 3. Sample frequency difference MFP results using KAM11 LFM pulse measurements. The receiving array is on the left and the white circle marks the location of the source (range = 3 km, depth = 60.2 m). An unambiguous MFP peak occurs very near the source range and depth. The origin of the auxiliary peaks at short range and at twice the range of the interesting peak is now under investigation.

IMPACT/APPLICATION

In broad terms, this project ultimately seeks to determine what is possible for a sonar system when environmental information is absent, incomplete, or uncertain. The capabilities of future Naval sonar systems will be enhanced when sonar techniques are developed that do not rely on detailed knowledge of the acoustic environment. Thus, this research effort into the effectiveness and utility of STR and unconventional MFP schemes may eventually impact how transducer (array) measurements are processed for detection, classification, localization, tracking, and identification of remote unknown

sound sources. In particular, the novel source localization results shown here may eventually provide a new means for the US Navy to localize and track acoustic sources of interest.

TRANSITIONS

The results of this research effort should aid in the design of sonar signal processing tools for tactical decision aids. At this time no direct transition links have been established with more applied research or development programs. Past Navy contacts for blind deconvolution with Dr. George B. Smith (NRL-SSC, retired) and Dr. Steve Finette (NRL-DC) are no longer active in this research area. The search for a transition path through NRL or one of the Navy's Warfare Centers continues. To this end, the PI does plan to visit ONR and to see Dr. Tague or another program monitor in Undersea Signal Processing within the next six months.

RELATED PROJECTS

This project currently uses acoustic array recordings of sounds that propagated through the ocean. In FY14, Dr. Heechun Song of SIO shared acoustic array recordings collected during the KAM11 experiment. The use of blind deconvolution and noise-reduction techniques for the recovery of free-field sound source signatures, sound levels, and transfer functions from measurements made in reverberant laboratory test facilities is also of interest for hydro-acoustic testing at the Naval Surface Warfare Center - Carderock Division which is supporting the UM NEEC acoustics student team and the laboratory water-tank experiments mentioned above.

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HONORS AND AWARDS

Prof. Dowling was invited to contribute an article on acoustic remote sensing to *Annual Review of Fluid Mechanics*. This article will appear in early 2015.